

Information processing with topologically protected vortex memories in exciton-polariton condensates

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We show that in a non-equilibrium system of an exciton-polariton condensate, where polaritons are generated from incoherent pumping, a ring-shaped pump allows for stationary vortex memory elements of topological charge $m = 1$ or $m = -1$. Using simple potential guides we can choose whether to copy the same charge or invert it onto another spatially separate ring pump. Such manipulation of binary information opens the possibility of a new type processing using vortices as topologically protected memory components.

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Introduction.— The exciton-polariton Bose-Einstein condensate [1] (BEC) in planar microcavities has become subject to much research and study [2] in the past decade with the promise of polariton condensation happening at much higher temperature than atomic condensates [3, 4]. BECs are low temperature systems of integer spin bosons in which, below a certain critical temperature, a large fraction condense to the ground state and become macroscopically coherent [5]. Being supercooled quantum systems, they offer a wide variety of topological phases and excitations such as the quantum vortex which will be the main focus in this letter.

The exciton-polariton is a quasiparticle formed by the strong coupling of a microcavity photon mode to electronic excitations in quantum wells embedded in a microcavity. The most notable features of this composite bosonic particle is its light effective mass (about 4 to 5 orders smaller than the electron mass) which arises from the photonic component, and strong binary interactions from the excitonic one. Polaritons also have a short lifetime (few orders of picoseconds), which inhibits thermalization to the lattice temperature. However, polariton-polariton scattering processes allow polaritons to relax fast enough into a macroscopically occupied ground state, effectively creating a polariton condensate [6].

The quantum vortex is one of the most well studied topological defects in atomic BECs and has been observed in both polariton parametric oscillators [7–9] and non-resonantly excited polariton BECs [10, 11]. These defects consist of a vortex core, where the condensate density reaches its minimum and phase becomes singular, and a circulating superfluid flow around, with phase winding being an integer number of 2π [5]. Its topological stability makes the vortex a prime candidate for a robust binary memory component, and recent works have considered control of the path of moving vortices [12–16].

In this paper we show that stable vortex solutions of charge $m = \pm 1$ are supported by an incoherent ring

shaped pump. Such pump shapes were considered experimentally, demonstrating pattern formation [17, 18], evaporative cooling [19] and vortex-antivortex arrays [20]. The vortices that we predict represent multistability in the system and are challenging to observe experimentally due to the random selection of the vortex sign during condensation, which is averaged to zero in multishot experiments. Nevertheless, one can expect that coherent pulses can deterministically select the vortex sign allowing their detection [21]. Alternatively, it was recently shown that very high quality microcavities can be used to make single shot measurements, allowing vortex detection in ring shaped traps [22]. Vortex states can be read by using interferometry [10], while other methods have been discussed in Ref. [23], such as detection of the wavevector of polaritons around the vortex core.

Using simple potential guides shown in figure 1, we find that a vortex charge can be both copied or inverted to a second spatially separate ring pump even under a large amount of random noise. Therefore satisfying the standards of copying binary memory, with high fidelity, and of a NOT gate. The choice of whether transferring the same charge ($\pm 1 \rightarrow \pm 1$) or the inverse charge ($\pm 1 \rightarrow \mp 1$) can be controlled by either changing the length scales of the potential guide or the distance between the ring pumps.

Theoretical Model.— Using mean field theory and assuming the spontaneous formation of the exciton-polariton condensate, an open-dissipative Gross-Pitaevskii (GP) model describes our incoherently pumped condensate coupled with an exciton reservoir. The polariton order parameter Ψ is described by a GP-type equation and the exciton reservoir density n_R by a rate equation [24].

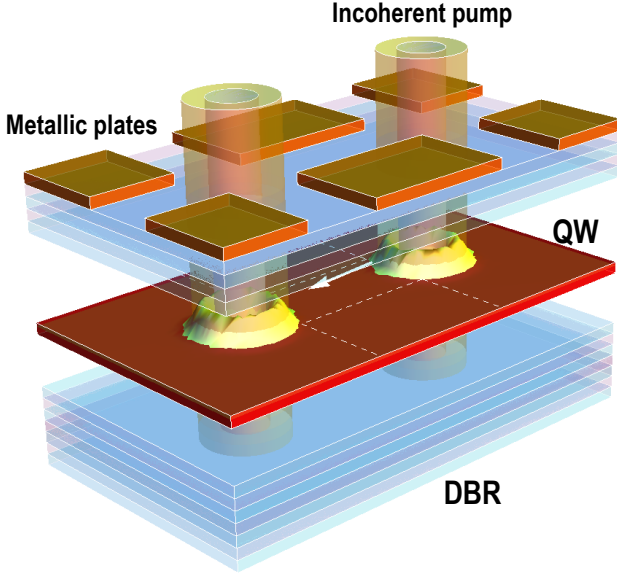


FIG. 1: (Color online) A schematic showing the exciton-polariton microcavity with ring-shaped incoherent optical pumps. The pumps create a ring-shaped exciton reservoir which in turn generates polaritons which form a vortex state. A grid like pattern of metallic plates helps to guide the polaritons from one pump to another.

$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-\frac{\hbar^2}{2m} \nabla_{\perp}^2 + V(\mathbf{r}) + g_c |\Psi|^2 + g_R n_R(\mathbf{r}, t) + i\frac{\hbar}{2} (R n_R(\mathbf{r}, t) - \gamma_c) \right] \Psi + P_c(\mathbf{r}, t) \quad (1)$$

$$\frac{\partial n_R}{\partial t} = -(\gamma_R + R |\Psi|^2) n_R(\mathbf{r}, t) + P_R(\mathbf{r}). \quad (2)$$

Here the kinetic energy of polaritons is characterized by effective mass, m . $V(\mathbf{r})$ represents any potential patterning of the microcavity, which can be achieved by a variety of techniques, such as: reactive ion etching [25–27], mirror thickness variation [28] and metal surface deposition [29, 30]. The constants g_c and g_R characterize the strengths of polariton-polariton and polariton-reservoir interactions, respectively. R defines the condensation rate, while γ_c and γ_R represent the decay rates of polaritons and reservoir excitons, respectively. We allow for both incoherent (non-resonant) pumping, $P_R(\mathbf{r})$, as well as resonant coherent pumping $P_c(\mathbf{r}, t)$.

Bistability of vortices under ring shaped pumping.— Let us first consider the case of a ring-shaped incoherent pump, in the absence of any potential ($V(\mathbf{r}) = 0$). The ring pump profile can be described by the function type:

$$P_R(r) = P_{R0} \left(\frac{r}{w_1} \right)^{10} e^{-(r/w_2)^2}. \quad (3)$$

where $r = \sqrt{x^2 + y^2}$. Owing to the many particle interaction effects the incoherent pump induces a blue shift

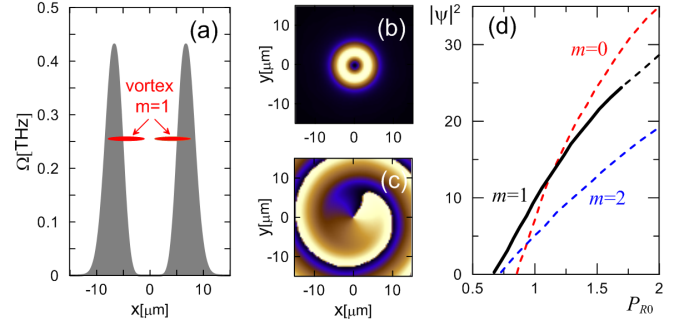


FIG. 2: (Color online) (a) Frequency shift (blue shift) induced by the ring shaped incoherent pump. (b) Density profile $|\Psi|^2$ of the vortex with charge $m = 1$ and its phase profile (c) for $P_{R0} = 1 \text{ ps}^{-1} \mu\text{m}^{-2}$. (d) Bifurcation diagrams of different states supported by the ring pump. Maxima of the polariton density $|\Psi|^2$ versus pump amplitude P_{R0} . Dashed lines represent unstable solutions.

in the frequencies of the polaritons $\Omega(r) = g_R n_R / \hbar = g_R P_R(r) / (\hbar \gamma_R)$, shown in figure 2 (a). It is found that the ring-shaped pump supports a stable vortex solution of charge $m = \pm 1$, provided that the pump intensity overcomes some threshold value [Figs. 2 (b) and (c)]. In general, among these fundamental vortices (with charges $m = \pm 1$) the ring-shaped pump also supports the solutions with other charges including a non-vortex state with $m = 0$ [Fig. 2(d)]. The latter one is characterized by the formation of the polariton condensate in the center of the ring pump. Similar solutions have been observed recently in [18, 19]. A standard linear stability analysis has been performed to prove stability of the solutions. It turned out that non-vortex solutions as well as vortices with the charge $m = \pm 2$ are unstable for our particular parameters of the ring pump (this is in contrast to the stability of $m = \pm 2$ vortices injected in polariton parametric oscillators with small momentum [31, 32]). The fundamental vortices with charges $m = \pm 1$ are the only stable solutions and experience destabilization for very high pumping rate [for $P_{R0} \gtrsim 1.7$ in Fig. 2(d)]. The vortex solutions with $m = +1$ and $m = -1$ are equivalent and can be used for bistability schemes. Note that the ring shaped pumping is essential; Gaussian shaped pumps are known not to support stable vortices in the steady state [33].

Operations with vortex states.— We now introduce $V(\mathbf{r})$, describing the potential guides which can be achieved using metallic layers, as shown in figure 1, which blueshift the polaritons. The parameters chosen for our system correspond to the experimental results of [34]. The polariton mass is set to $m = 10^{-4} m_e$ where m_e is the free electron mass. The decay rates are chosen as $\gamma_c = 0.033 \text{ ps}^{-1}$ and $\gamma_R = 1.5 \gamma_c$. The interaction strengths are set to $g_c = 6 \mu\text{eV} \mu\text{m}^2$ and $g_R = 2g_c$, and condensation rate to $R = 0.01 \text{ ps}^{-1} \mu\text{m}^2$.

All results displayed in this paper were done with both

random initial conditions and a small background of random noise [35] in order to test the robustness of our results. We start by creating a vortex with either charge 1 or -1 . Under an incoherent pump, the vortex charge is chosen spontaneously. In order to write vortex states with a definite sign, an additional coherent pulse is applied. The coherent pump can be written:

$$P_c = P_{c0} \exp \left[- \left(\frac{\mathbf{r} - \mathbf{r}_c}{w_c} \right)^2 - i \left(\frac{E_c t}{\hbar} - \mathbf{k}_c \cdot \mathbf{r} \right) \right]. \quad (4)$$

Here the pump energy is $E_c = 0.18$ meV, the momentum $|\mathbf{k}_c| = 0.46 \mu\text{m}^{-1}$ and the amplitude $P_{c0} = 0.3$ meV μm^{-1} . In order to start the circulating flow of polaritons, the coherent pump is placed a small distance \mathbf{r}_c away from the center of the ring pump (yet staying inside the ring) and a clockwise or anticlockwise circulation is created by satisfying $\pm \mathbf{k}_c \cdot \mathbf{r}_c = 0$.

The results of creating a stationary vortex state can be seen stepwise in figure 3. The incoherent ring pump is placed equidistant from the potential squares giving the scheme a $\pi/2$ symmetry. The coherent pump placement is shifted slightly from the middle of the ring pump center to optimize the flow of the injected polaritons. Starting both the coherent- and incoherent pump at the same time, we observe a quick injection of polaritons into the system that starts to rotate. After 50 ps we shut off the coherent pump and allow the system to reach a stationary state. After a few hundred picoseconds the vortex becomes cylindrically symmetric and stable, maintaining its form for as long as the continuous wave ring shaped pump is applied.

We show that by using simple potential guides of different length scales to manipulate the flow of polaritons, it's possible to copy the same (or inverted) vortex state by activating a second spatially separate incoherent ring pump. Furthermore, if the blue shift of the potential squares is substantially changed then so does the polariton flow pattern in the guides, opening the possibility of controlling the information transfer by having different types of metallic layers on the microcavity. The distance between the two pumps must be chosen such that they can interfere accordingly with each other. If the distance is too small, then polaritons from each pump interfere strongly and the vortex states are lost. If the distance is too great, random noise will overcome the polaritons traveling in the guide.

We now describe the method of copying the same or inverted vortex state from one pump to another. The potential guide is set to the desired length scales and on one side a ring pump is activated with a vortex state of either $m = \pm 1$ chosen by coherent pumping as shown in figure 3. As the initial vortex settles and becomes stable after 500ps, we activate a second ring pump with strong random polariton noise in its center as an initial condition. If it were alone, the second ring pump would develop into

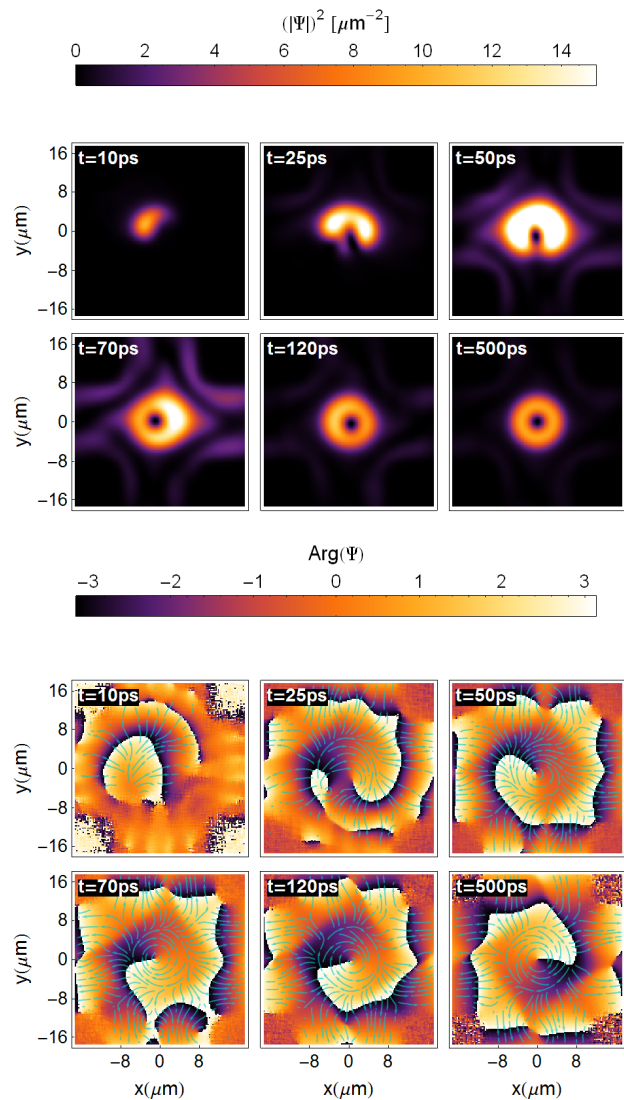


FIG. 3: (Color online) Polariton density and phase plots respectively showing the generation of a vortex with charge $m = -1$ by coherent pumping at $x = -3.7 \mu\text{m}$ in a potential grid. Both the coherent pump and the incoherent ring pump are activated at the same time and after 50 ps the coherent pump is shut off. At 500 ps the polaritons have formed a stable vortex state. Density streamlines are plotted along with the phase profiles (blue arrows). Trails of polaritons can be clearly seen as they diffuse away along the potential grid points. The grid bulk energy is set to $V_0 = 1$ meV, and $P_{R0} = 1 \text{ ps}^{-1} \mu\text{m}^{-2}$.

a vortex state with sign chosen spontaneously as polaritons condense. However, polaritons travelling from the first vortex state arrive at the second with a definite momentum, which depends on the sign of the first vortex state. As in the case of writing the vortex state with a coherent pulse, these polaritons introduce a preferential direction of flow at the position of the second ring shaped pump, which overcomes any noise in the system. This allows the second vortex state to form in a way logically

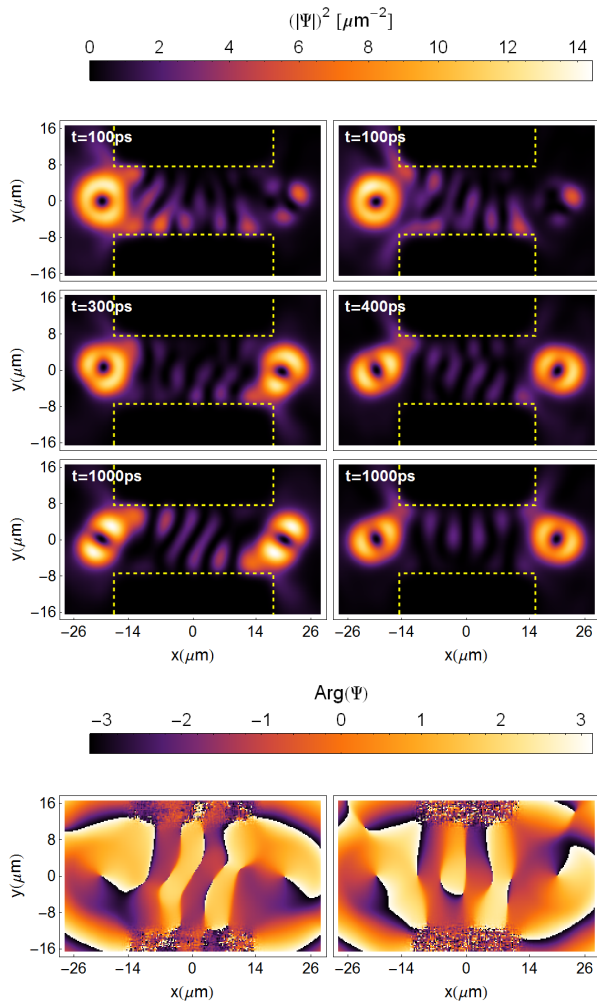


FIG. 4: (Color online) **Left column:** Density plots of the copier process taking place at different times. Yellow dashed lines show the edges of the guide. At $t = 300$ ps the transfer is complete and at $t = 1000$ ps the state is nearly stationary. **Right column:** The inverter process taking place at different times. At $t = 400$ ps the transfer is complete and at $t = 1000$ ps the state is nearly stationary. Bottom panels show the phase profiles at $t = 1000$ ps.

dependent on the state of the first. Multiple trials with different realizations of stochastic noise reveal that the transfer occurs with 100% fidelity.

Results are presented in figure 4 where the yellow dashed lines outline the edges of the guides. We observe the formation of a vortex in the second pump with an inverted charge with respect to the charge of the initial vortex (see figure 4, top and bottom left frames). We call this process an *inverter*, $m_1 = \pm 1 \rightarrow m_2 = \mp 1$. In the left column of figure 4, we observe, for different guide length scales, the formation of a vortex in the second pump with the same charge with respect to the charge of the initial vortex. We call this process a *copier*, $m_1 = \pm 1 \rightarrow m_2 = \pm 1$. One can see that in both cases the

vortex states become deformed in a dipole manner corresponding to the flow pattern of the polaritons between the pumps.

The two different transfers never take longer than 1 ns. Numerous trials revealed the same results under a large amount of random noise added to the second pump on its activation (indicating that the transfers are robust). We expect that faster transfer times can be achieved in microcavities with shorter polariton lifetime or lighter polariton effective mass.

The *copier* and *inverter* processes can be realized using a periodic grid of potential squares with guides in all four directions and ring pumps at the grid nodes. We observe that the two processes can be controlled when the pumps are shifted from the nodes, i.e. changing the distance between them. Using these results, we can start with any vortex state in one node and transfer either the inverted or same state to any other node in the grid by simply controlling the distance between the pump centers at each guide. Also, for simplicity, we have neglected the spin degree of polaritons. We expect that the half-vortices that form in spinor polariton condensates [11, 36, 37] can offer a wider alphabet for topologically protected spin based logic. Future work should focus on the adaptation of vortex bits for use in cascable logical circuits [38].

Conclusion.— We have shown that it's possible to sustain a stable vortex state of charge $m = \pm 1$ in an open-dissipative system of exciton polaritons using an incoherent ring shaped pump. These vortex states can furthermore be copied to a different ring pump using simple potential guides. The choice of copying the same charge or the inverted charge can be controlled by either changing the length of the guides or the distance between the pumps. We believe that a new playground of future mechanism can be created using these basic *inverter* and *copier* schemes as building blocks.

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